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Office of Scientific Research and Development
NATIONAL DEFENSE RESEARCH COMMITTEE
Section 16.1 - Optical Instruments

Carnegie Institution of Washington
Mount Wilson Observatory

Final Report on

SHUTTER DEVELOPMENT FOR AERIAL PHOTOGRAPHY

I. Langer Multiple-Slit Shutter

II. Modification of 24" K-17 Shutter

Contract No. OEMsr-101
March 15, 1945

Section 16.1 Report No. 90
O.S.R.D. Report No. 4739
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See Also:
Modification of the Metrogon Shutter
Section 16.1 Report No. 35
November 1, 1943

FOREWORD

Under Project AC-29, NDRC was asked to develop a multiple-slit focal plane shutter of the type proposed by Dr. R. M. Langer, in the hope that the distortion, non-uniformity of exposure and limited life which are ordinarily associated with focal plane shutters would be reduced.

In this shutter the exposure is made by moving a primary screen with parallel slots. A secondary screen, with wider slots, but with the same center-to-center spacing, protects the film before and after the exposure, and moves during the exposure in such a way as to permit light to pass through slots in the primary screen.

There is inevitably a narrow strip at the boundary between the regions exposed by adjacent slots which receives exposure from both slots. Although the time interval between the two exposures can ordinarily be held below 1/100 second, perceptible doubling of the image may exist in these boundary regions. The combined area over which this doubling occurs can probably be held to less than 10% of the total area of the photograph, and in any case the doubling will be noticeable only when image motion is considerable. It should be noted that blurring of almost the same amount occurs over the entire photograph with present between-the-lens shutters operating at 1/150 second. Actually, doubling may be preferable to blurring, since it has less effect on recognition of detail.

Two methods of relating the mechanical motions of the two screens are of particular interest. In one (Type 2 of the present report), the primary and secondary screens are linked together and travel with a fixed ratio of speed (approximately 2:1). As a result, the film is uncovered gradually and there is a region of appreciable width within which there is double exposure. The mechanical linkage is, however, very simple and strips of uneven density can easily be reduced to an unobjectionable level, which can be still further reduced by printing through a compensating screen. This linkage was used in the first model of the multiple-slit shutter, which was built for preliminary tests at the Mount Wilson Observatory and is described in detail in the present report. In view of the simplicity of the mechanism, and in view of the fact that there are no critical requirements relating to the motions of the two screens, it would be very desirable to develop an improved model of this type.

In the other design (Type 1), the slits in the primary screen move out from under the bars in the secondary screen before the secondary screen starts to move. At the end of the exposure, the secondary screen is stationary while the slits in the primary screen move under it. The result is a narrower region of overlapping exposure, but the requirements for accurate relative motions of the screen are much higher. A shutter based on this principle has been developed by the Technicolor Motion Picture Company, and is described in Section 16.1 Report No. 57, OSRD Report No. 4184.

The present report describes also a modification of the 24" K-17 shutter which reduces the exposure from 1/150 second to 1/210 second. This 30% increase in speed is accomplished by substituting a triple spring for the present single spring. It seems likely that this modification would be satisfactory if certain minor changes are made, and if the tendency of the shutter leaves to interfere on closing can be overcome.

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Room 7, Gray's Hall
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June 11, 1945

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I. LANGER MULTIPLE-SLIT FOCAL PLANE SHUTTER.

Abstract

A new type of focal plane shutter, which uses several parallel slots instead of a single slot, has been developed and a test model built. The performance to be expected from such a shutter is compared with that of a conventional focal plane shutter.

Two types of motion of the proposed shutter are analyzed, and their advantages compared.

Design of the test model is described. A photograph made with this shutter is reproduced, and its characteristics discussed.

A. Introduction.

Under directive AC-29 the Army Air Forces requested NDRC to develop a fast shutter of the louvre type. This was intended for use with new lenses of long focus in which a between-the-lens shutter of sufficient speed could not be mounted. However, the inherent disadvantages of the louvre shutter, together with the difficulties which had been experienced both within Section 16.1 and at California Institute of Technology in designing large aperture louvre shutters of the required speed, suggested that a more satisfactory result could be obtained by a focal plane shutter of new design. The result is the multiple-slit focal plane shutter, the theory of which was developed in some detail at the Mount Wilson Observatory. A model of such a shutter was built here in 1942 and tested successfully. The present report covers this work, but does not include later development of the idea, which was carried on elsewhere.

B. General Characteristics of the Multiple-Slit Shutter.

The proposed shutter replaces the single slot of the conventional focal plane shutter by a series of uniformly spaced parallel slots. The exposure is made by moving the curtain approximately the distance between slots. Each slot then serves to expose a strip of film, the combined action exposing the entire picture. Since the slots are in general in the field before and after the exposure, means are provided, in the form of a secondary screen, for uncovering the slots at the beginning of the exposure and covering them again at the end.

Comparison of Proposed and Conventional Focal Plane Shutters.

The new design has the usual advantages of focal plane shutters as distinguished from most other types of shutter, in that very short exposures are possible and that the same shutter can be used with a variety of lenses, including those of large diameter.

The relation between efficiency, effective shutter speed and total time open is controlled by the same factors as in ordinary focal plane shutters, and need not be discussed in this report.

Conventional focal plane shutters are subject to three principal disadvantages which until recently have restricted their use in aerial photography. These are distortion, non-uniform exposure, and unreliability under conditions of extremely low temperature. All of these disadvantages are associated with the fact that the exposure is made by moving a single slot across the entire width of the film.

This means, in the first place, that there is an appreciable period of time between the exposure of one edge of the picture and that of the other. Any motion of the image in the focal plane of the camera during this time results in distortion of the picture. In aerial photography the ground speed of the plane produces distortion of this sort which is uniform and predictable, and which can therefore be compensated, at least in theory, during the printing of the pictures. However, oscillation of the camera or irregular motion of the entire aircraft leads to distortion of a complex and unpredictable sort. Aerial photographs taken with a focal plane shutter are therefore not suitable for accurate map-making. They may also be unsatisfactory for reconnaissance in which pictures are to be viewed stereoscopically, since the distortion may cause apparent hills and valleys which are difficult to distinguish from real ones.

In the second place, in the conventional focal plane shutter uniformity of exposure requires that the slot in the curtain move all the way across the film at a constant speed. Ordinarily it is driven by a spring and accelerates during the exposure. A mechanism could doubtless be built which would produce more nearly uniform motion, but the difficulty of doing this is greater the longer the travel of the curtain.

Thirdly, the travel of the slot all the way across the film necessitates the use of a flexible screen, since it would otherwise extend far beyond the normal dimensions of the camera. Rapid flexing of available materials, especially at very low temperatures, leads to reduced life and impairs the reliability of the shutter.

In the proposed shutter these disadvantages are either avoided or greatly reduced. For a given exposure time and width of slot the speed of the screen is the same with this and the conventional shutter. However, the distance of movement is reduced by a factor approximately equal to the number of slots. The time interval during which all parts of the field are exposed is correspondingly reduced, and with it the possibility of distortion. Since the number of slots can be ten or more, the remaining distortion should be negligible for most purposes. The overall distortion over the film is eliminated since the exposure is simultaneous in all the slots, and these are distributed over the whole field. Thus extended objects retain their general size and shape and are distorted only locally in small sections. What distortion remains is likely to be of a simple type, since there is little time for changes in camera motion to occur. The repetition of the distortion in the strips of film exposed through the separate slots eliminates any possibility of errors in stereoscopic interpretation.

Due to the shorter travel, the new shutter can use non-flexible screens if desired, thus eliminating rollers and increasing the strength and durability of the shutter. Uniform motion of the screens, and hence uniform exposure over the whole field, should be approached more closely. More rapid acceleration should be possible with metal screens than with flexible ones, thus permitting even shorter exposures should these prove desirable.

It should be pointed out that focal plane shutters used in present aerial cameras have the curtain so far from the film that when fast exposures are used the efficiency is very low, giving less reduction of plane motion than should be obtained from exposures of this speed. An interesting possibility is that a multiple-slit shutter might be designed in which the two screens extend inside the frame of the standard film magazine. This would allow the distance from shutter to film to be reduced very appreciably, increasing the motion-stopping effectiveness of the shutter for a given speed. This could be done without discarding present standard magazines, and would probably require the sacrifice of only about 1/2" around the edge of the picture.

Regions of Overlap.

In exchange for these advantages, the multiple slit shutter has one principal disadvantage. Along each boundary between the area of film exposed through one slot and the area exposed through the adjacent slot is a narrow strip which receives part of its exposure through one and part through the other. This may result in two distinct faults, and most of the problems of design and construction of such shutters arise from the effort to minimize these faults and to achieve the best compromise between them.

In the first place, unless the mechanical motions are planned and performed correctly, the sum of the two exposures received by points in the areas of overlap will not add up to the exposure received by the rest of the film. This results in a barred appearance of the negative or of a direct print from it. Although this is disturbing aesthetically it does not necessarily reduce the military value of the picture. This effect is more easily avoided if the area of overlap is made relatively wide, since the exposure gradients within it are then more gradual. The irregularities can be greatly reduced if desired during the printing, as will be shown presently.

The second effect of the areas of double exposure is the possible doubling of the image within these areas. The part of the exposure which is made through one slot occurs just as that slot is being uncovered near the beginning of its motion, while the exposure through the adjacent slot does not occur until near the end of the motion as the slots are being covered again. Any net motion of the image in the focal plane during this interval will therefore displace the second image relative to the first. This doubling gives a measure of the total distortion across each section of the picture.

If the displacement of the image is slight it will be apparent only as a loss of definition in the strips affected. If the motion is great, two distinct images may be visible, so that interpretation will not be seriously handicapped. In intermediate cases the value of the picture will be reduced in proportion to the area affected. It is therefore an advantage from this point of view to keep the regions of overlap as narrow as possible. Since aerial photographs are ordinarily taken in series with considerable duplication for stereoscopic viewing, this fault may prove less serious in practice than in theory.

C. Suggested Types of Motion.

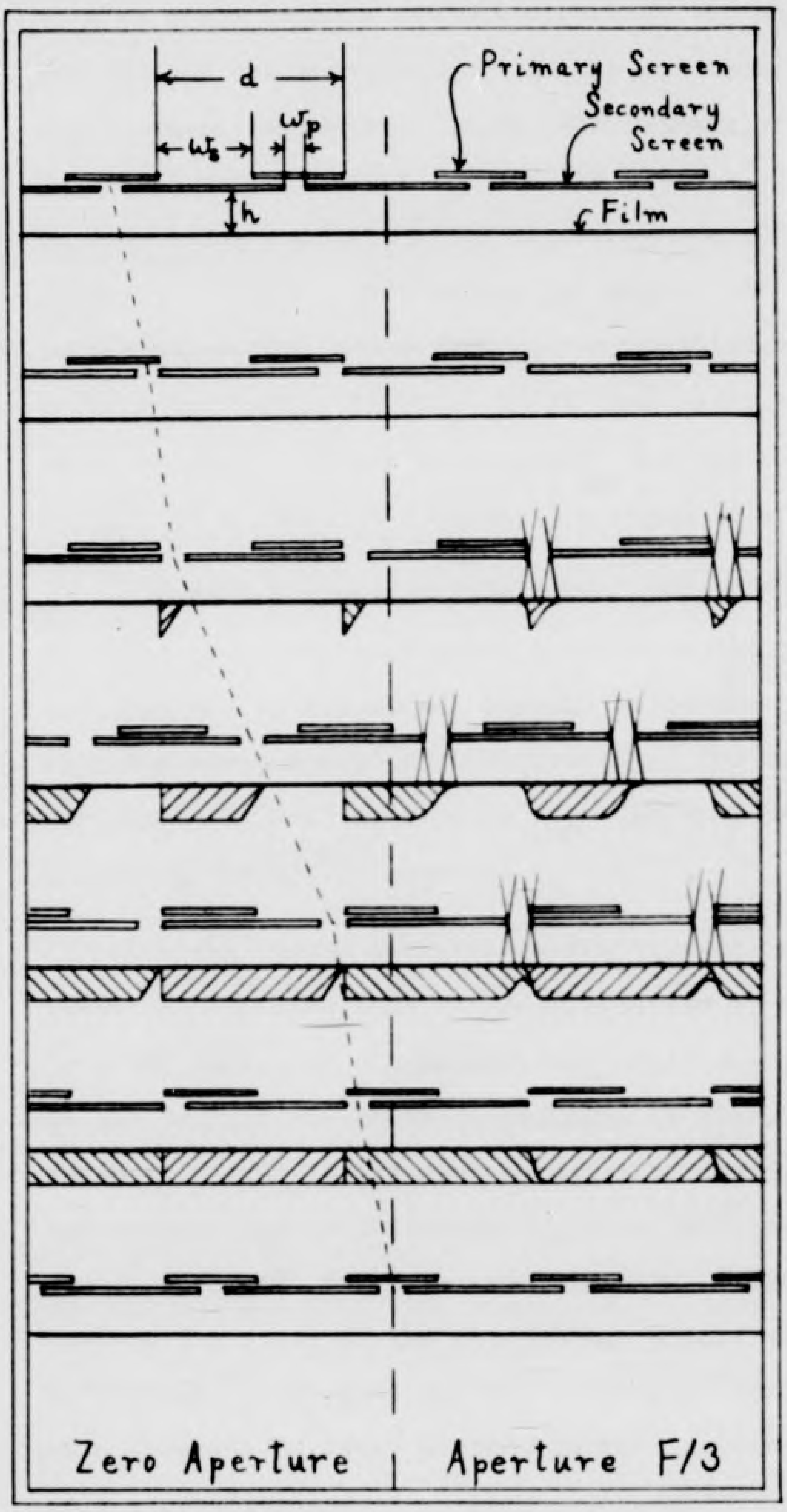
Only two of the many possible types of motion of the primary and secondary screens will be discussed in detail. In both cases the slots are assumed to be equally spaced, the distance between centers being d for both screens. The exposure is determined by the width w_p of the slots in the primary screen, and by its velocity of travel V_p, which is considered constant throughout the exposure. Just as in a conventional focal plane shutter, the effective exposure time T_e is given by

$$T_e = w_p/V_p \qquad (1)$$

The secondary screen serves only to uncover the openings in the primary screen as the exposure begins, and to cover them again as it ends. Since the width w_s of the secondary slots is several times w_p, the exact motion of the secondary screen during the greater part of the travel is immaterial. The two cases to be discussed involve fundamentally different types of motion of the secondary screen at the beginning and end of the exposure. This determines the type of overlap between the areas exposed through adjacent slots.

Type 1. Secondary Screen Stationary at Start and End of Exposure.

Analytically the simplest arrangement is for the secondary screen to be held stationary while the primary slots are being uncovered and again while they are being covered. Figure 1 shows the situation schematically at selected moments during an exposure. The primary screen is shown a distance h above the film, with the secondary screen just above it. In the diagram $w_s = d/2$, although other



	Total Screen Motion		Time from Position (2)
	x_p	x_s	t
1	0	0	—
2	$\frac{d-w_s-w_p}{2}$	0	0
3	$\frac{d-w_s+w_p}{2}$	0	$\frac{w_p}{V_p}$
4	$d-\frac{w_s}{2}$	$\left[\frac{d-w_s}{2}\right]$	$\frac{d+w_p}{2V_p}$
5	$\frac{3d-w_s-w_p}{2}$	$d-w_s$	$\frac{d}{V_p}$
6	$\frac{3d-w_s+w_p}{2}$	$d-w_s$	$\frac{d+w_p}{V_p}$
7	$2d-w_s$	$d-w_s$	—

Figure 1. Shutter Screen Motion, Type 1

choices could be made without affecting the analysis. In (1) the two screens are shown at rest in the positions they normally occupy between exposures. In (2) the primary screen has been accelerated to full speed V_p, and the slots w_p are just starting to be uncovered, initiating the exposure. In (3) slots w_p are entirely uncovered. Immediately following this the secondary screen is set in motion, moved through the position shown in (4), and brought to rest as in (5). It is then ready to cover the primary slots as they continue their motion through (6) and come to rest in (7) in a position similar to that of (1).

At the right of Fig. 1 are given for each position the distance that each screen has moved from its initial position (1), and also the time that has elapsed since the start of the exposure when the screens were at position (2). The time needed between positions (1) and (2) depends upon the type of drive used, and is of little practical interest.

The shaded areas below the line of the film indicate the amount of exposure that has been received at each point on the film from the beginning of the exposure until the moment illustrated. To the left of the heavy broken line is shown the ideal case in which all light is incident normally to the film. To the right of the broken line is indicated the more realistic case of a lens of finite aperture, taken as F/3. Pencils of light are shown passing through the slots at the two extreme angles of incidence. (The difference in level of the two screens is here neglected.) In this case the exposure pattern is more complex, and is indicated only schematically.

It is clear that for this motion of the screens the area of overlap is caused entirely by the finite solid angle subtended by the lens at the film. The width of overlap is proportional to lens diameter and to the distance h from film to primary screen, and is inversely proportional to the focal distance. It does not depend upon the dimensions of either the primary or the secondary slots. For h = 1/4" and lens aperture F/5, the regions of overlap are 1/20" wide.

It should be noted that only in the central part of this overlap are the two exposures nearly equal. At the edges, where one exposure is much weaker than the other, the clarity of the picture will not be destroyed even if the two images are not in perfect register. If the distance d between strips is 1", the areas of overlap will occupy 1/20 of the total area of the picture, but any doubling of the image in these areas will be troublesome in only the central part of each area, or about 1/30 of the picture. This should be an acceptable loss if the definition is improved over the remaining 29/30 of the field by use of the fast shutter.

Choice of the width of the secondary slots w_s will depend upon the following considerations: as w_s becomes larger relative to d, the primary screen has less space in which to be accelerated to full speed, and also less space in which to be brought to rest again; the secondary screen travels a shorter distance between situations (3) and (5), but its motion must match that of the primary more closely to avoid obstructing the primary slots.

A possible way of moving the secondary screen is to connect it by a latch of some sort to the primary screen so that it will be picked up immediately after position (3) in Fig. 1, and dropped off before position (5). The danger in this method is that the primary screen will be slowed by the inertia of the secondary, causing bands of over-exposure. It seems likely that independent sources of power should be used for the two screens, the secondary being in effect released by the primary as it passes, but not carried along by it.

Satisfactory use of this type of motion depends upon the success with which the secondary screen can be stopped accurately in the correct position. If it goes too far, for example, the primary slots will be left open too long, and parallel bands of over-exposure will result. The narrower the regions of overlap are made (as by reducing h or by stopping down the lens) the more sensitive the exposure in these regions becomes to inaccuracy in the position of the secondary screen.

In summary, the advantage of this type of motion is that the areas of overlap are kept narrow, which is important if the camera moves enough during the exposure to cause noticeable doubling of the image in these areas. The main disadvantage appears to be that uniform exposure within the areas of overlap may be hard to achieve. The driving mechanism must be well designed, well made, and accurately adjusted.

Type 2. Secondary Screen in Uniform Motion.

Construction of the operating mechanism is simplified if the two screens always move in such a way that their velocities have a fixed ratio. This can be accomplished, for example, by connecting both screens to a pivoted arm. If the connections are made at distances r_p and r_s from the pivot, then the ratio of the two screen velocities is

$$V_s/V_p = r_s/r_p.$$

The velocity of the primary screen is essentially fixed by the desired exposure time and by w_p, in accordance with equation (1). The velocity of the secondary relative to the primary is fixed by the ratio of d and w_s. For in order to expose the whole field uniformly, the primary screen must move a distance d between the time the slits are half uncovered and the time they are half covered again. During this interval the secondary screen, if it is to perform its function of covering and uncovering the primary slots, must either gain or lose a distance w_s relative to the primary. The ratio of velocities must therefore be either

$$\frac{V_s}{V_p} = \frac{d + w_s}{d}$$

or

$$\frac{V_s}{V_p} = \frac{d - w_s}{d} \qquad (2).$$

In practice the second case will ordinarily be chosen both because it gives narrower regions of overlap and because less driving energy is required.

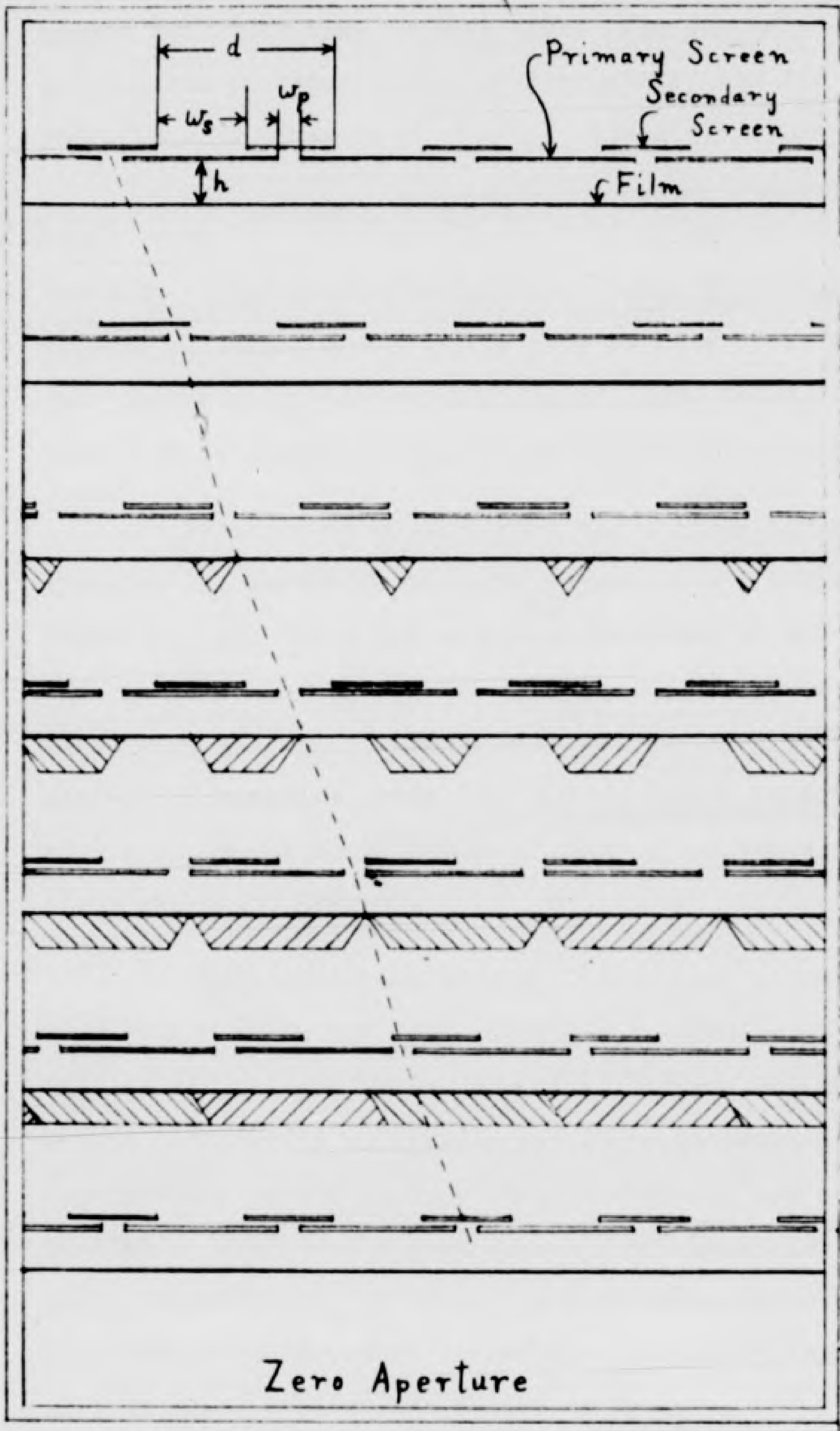
Figure 2 shows positions of the two screens at instants corresponding to those of Figure 1. Again w_s is taken as d/2, though this choice is not necessary.

The region of overlap with this type of motion is wider than with Type 1. For light incident normally, its width is $D = V_p t_1$, where t_1 is the time required for the primary screen to move a distance w_p relative to the secondary, or $t_1 = \frac{w_p}{V_p - V_s}$. Using (2), this becomes

$$D = \frac{w_p V_p}{V_p - V_s} = \frac{w_p}{1 - V_s/V_p} = \frac{w_p d}{w_s} \qquad (3).$$

To reduce the overlap it is therefore advisable to make w_s as large as possible compared to d. This amounts to making the width $d - w_s$ of the strips of which the secondary screen is composed as narrow as is convenient. The limiting requirement here is that the strip width must be sufficient to prevent light from getting through the two screens when the shutter is closed. (To permit the use of narrower strips, a third screen might well be added below the primary. This might be driven at the same speed as the secondary screen and have slots of the same or slightly greater width.)

The effect of overlap is harmful only insofar as motion of the image has occurred during the elapsed time of the shutter



	Total Motion, x_p of Primary Screen: General Case	If $w_s = \frac{d}{2}$	Time from Position 2
1	0	0	—
2	$\frac{(d-w_s-w_p)d}{2w_s}$	$\frac{d}{2}-w_p$	0
3	$\frac{(d-w_s+w_p)d}{2w_s}$	$\frac{d}{2}+w_p$	$\frac{w_p d}{V_p w_s}$
4	$\frac{d^2}{2w_s}$	d	$\frac{(w_s+w_p)d}{2V_p w_s}$
5	$\frac{(d+w_s-w_p)d}{2w_s}$	$\frac{3d}{2}-w_p$	$\frac{d}{V_p}$
6	$\frac{(d+w_s+w_p)d}{2w_s}$	$\frac{3d}{2}+w_p$	$\frac{(w_s+w_p)d}{V_p w_s}$
7	$\frac{d^2}{w_s}$	$2d$	—

Motion of Secondary Screen

$$x_s = x_p \frac{d-w_s}{2}$$

Figure 2. Shutter Screen Motion, Type 2

motion t_s. This time is best taken from the half-open to the half-closed position of the primary slots, and for all simple cases this is given by $t_s = d/V_p$. Using (1), this becomes

$$t_s = T_e d/w_p \qquad (4)$$

where T_e is the effective exposure time. It is therefore advantageous to keep d small and to have as many slots as possible. The limit will be the possibility of light leaks, and also the fact that in general smaller d means higher accelerations.

From (4) it appears that for a given effective exposure there is one advantage in using wider primary slots, since this reduces t_s and hence the amount of doubling of the image. But this reduction of t_s results from the higher screen velocity which must accompany wider slots, and may lead to mechanical difficulties. Also, from (3), the region of overlap increases with w_p. On the whole narrow primary slots and wide secondary slots are to be favored.

Although motion of Type 2 necessarily gives more overlap than Type 1 there are very considerable advantages in it. Since the two screens are always positively linked together, a single source of power is sufficient and there is nothing to cause irregularities in the motion. Once the blades are correctly assembled on the lever system there is no reason for their getting out of adjustment. If errors of adjustment do occur, they cause less noticeable exposure differences in the regions of overlap than do equal errors with motion of Type 1.

About twice as much distance is available in which to accelerate the primary screen and get it up to speed. This means that if other factors are the same the acceleration need be only about half as great, requiring only half the driving force. Or, if the acceleration is the same in both types of motion, Type 2 permits a screen velocity which is larger by a factor of $\sqrt{2}$, or 1.41. This allows a correspondingly shorter exposure time.

D. Design and Construction of Test Shutter.

As a practical test of the preceding analysis, a model was built using the system of screen motion described as Type 2. This type of motion was chosen for the first trial partly because design and construction were inherently simple and straightforward.

Plate 1 is a photograph of this model from the side toward the lens. The shutter is intended to cover a film 6 1/4 by 8 1/4 inches, the slots running the short dimension. The 18 slots in each screen are 6 1/4 inches long and have a spacing between centers of d = 1/2". The width w_p of the primary slots is 1/16" and that of the secondary slots w_s is 1/4". The screens are 7 3/4" by 10 1/4" in size and are of duralumin sheet, 0.015" thick.

The main frame of the shutter is a steel plate 11 1/2" by 15 1/4" and about 3/8" thick. Near the lower corners of the plate are pivoted two levers which carry the shutter screens. They are linked together at the top by a light connecting bar, so that their motion is always identical. The two shutter screens are pivoted to these levers at distances r_p and r_s from the main pivots, so chosen that equation (2) is satisfied. That is,

$$\frac{r_s}{r_p} = \frac{V_s}{V_p} = \frac{d-w_s}{d} = \frac{1}{2} .$$

The shutter is driven by a coiled spring which is guided by a 1/2" round bar and acts against one of the supporting levers. This spring exerts a force of 12 pounds at the beginning of the stroke, decreasing nearly to zero at the end.

The upper and lower edges of the screens slide in grooves 1/16" wide which oblige them to move in a plane but do not restrict their motion within this plane. This is controlled entirely by the supporting levers to which they are pivoted. The screens therefore

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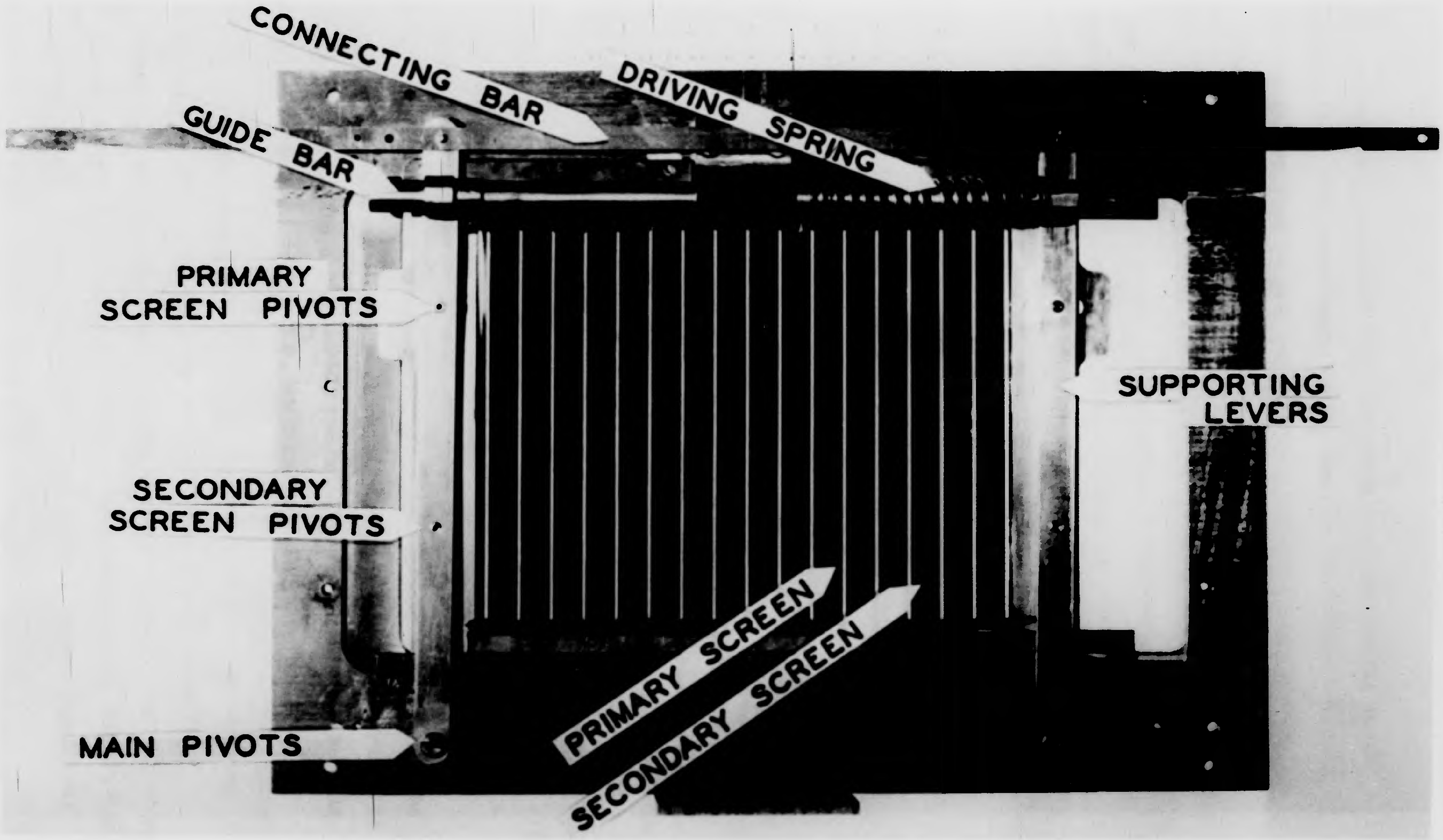


Plate I Test Model of Multiple-Slit Shutter

RESTRICTED

do not move in a straight line but along a slight curve, whose radius is r_p for the primary and r_s for the secondary. This is immaterial so long as the two systems of slots remain always parallel to the edge of the film.

The two screens are almost in contact, both running in the same grooves, and are prevented from interfering with each other by being very slightly bowed in opposite directions. The edges of one screen are reinforced and protected by strips of brass shim stock folded and clamped over them. The shutter is cocked by pulling the connecting bar to the left (in Plate 1) and securing it with a catch.

For the slot dimensions used, we find from equation (1) that to give an effective exposure time of 0.001 sec. the velocity of the primary screen must be $V_p = w_p/T_e$ = 62.5 inches per second, or 5.2 ft./sec. Before the slots begin to be uncovered the primary screen moves a distance of $\frac{d}{2} - w_p$ = 3/16". To reach a velocity of 5.2 ft./sec. in this distance requires a uniform acceleration of 870 ft./sec.^{2}, or 27 g.

From equation (3), the width of the regions of overlap between areas exposed through neighboring slots is $D = w_p d/w_s$ = 1/32" for light incident normally. For a lens working at F/5 and for a distance from film to primary screen h = 3/8", D will be increased by 3/40", giving a total overlap of slightly more than 0.1". The amount of doubling in the regions of overlap will be determined by the motion of the image during the time t_s from half open to half closed. This is d/V_p = 0.8, or 1/125 second.

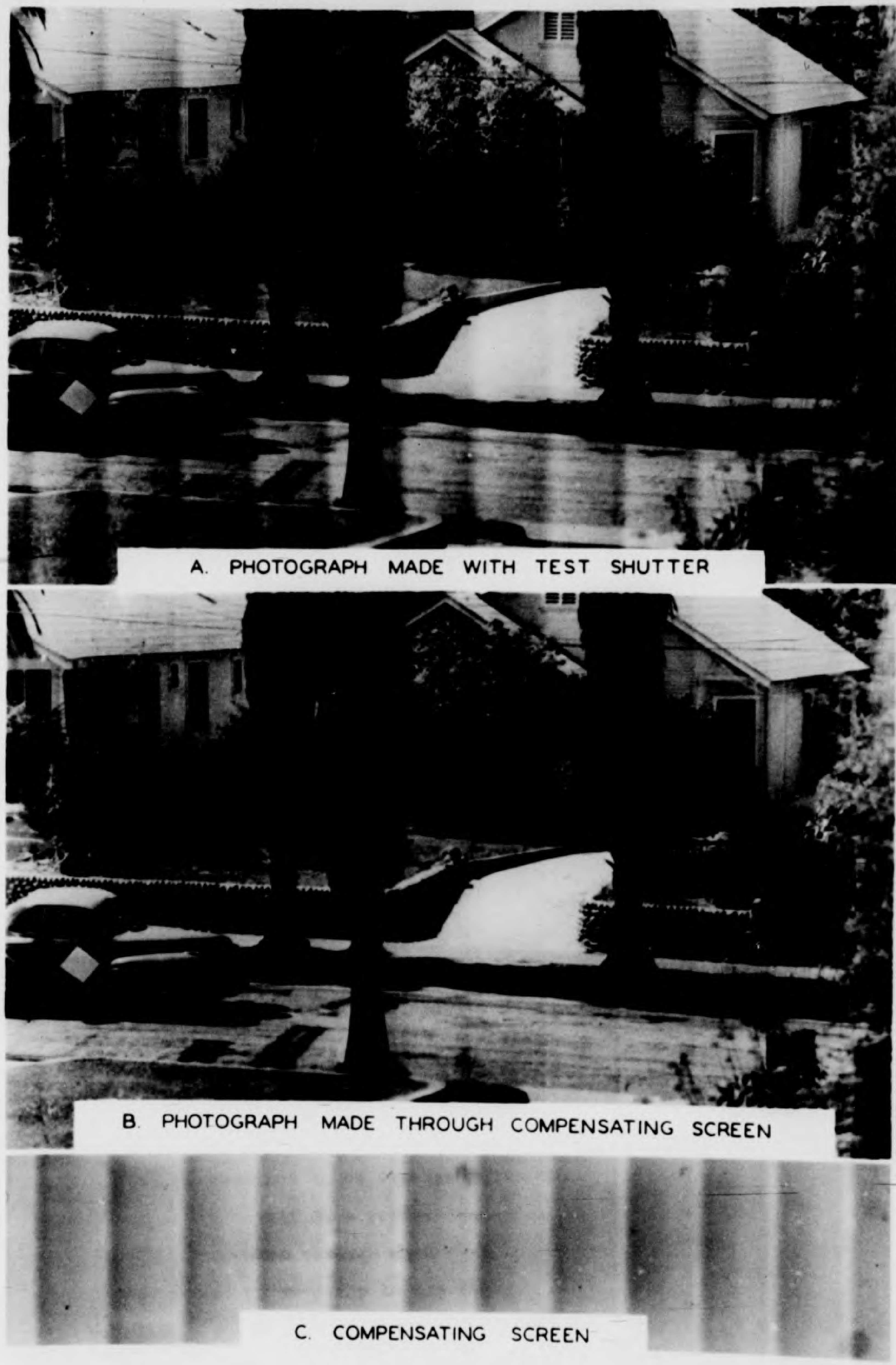
This model was originally intended to have two driving springs on the guide bar, one on each side of the supporting bracket. The shutter could then be operated first in one direction and then in the other. Also during part of the motion one driving spring would be operating against the other. It was hoped that this would reduce the tendency of the screens to continue to gain speed during the exposure. It was found that this scheme would not operate satisfactorily without more elaborate design, and only the single spring shown in Plate 1 was used for the photographic tests. Some constant speed device would presumably be included in the driving mechanism of any final design.

It will be clear from Plate 1 that the operating mechanism, although cumbersome in the present model, is fundamentally compact. The three levers of which it is composed are parallel to three edges of the picture and could be designed to occupy very little space outside the minimum dimensions of the camera itself. It should be possible to make a shutter of this type rather more compact than the conventional focal plane shutter.

E. Photographic Tests of Shutter.

To permit test exposures to be made as simply as possible, the shutter was mounted on a wooden box which served as camera. A Cooke Aviar lens of 20" focus and aperture F/5.6 was mounted in a focusing tube on the front of the box. Super XX cut film 6 1/4" by 8 1/4" was used in a regular film holder. Due to the metal adapter plate, the film surface was about 11/32" from the primary screen.

A typical photograph is reproduced in the upper part of Plate 2. This shows an automobile which was moving at a speed of about 20 mph (30 ft/sec) and was at a distance of 120 feet from the camera. The motion of the image of the moving car in the focal plane of the camera was greater than would normally be encountered in aerial photography. It would correspond to the motion caused by ground speed of a plane flying at 300 mph at an altitude of 1800 feet. Motion at the more typical altitude of 25,000 feet would therefore be only one fourteenth that of the car in the test photograph.



A. PHOTOGRAPH MADE WITH TEST SHUTTER

B. PHOTOGRAPH MADE THROUGH COMPENSATING SCREEN

C. COMPENSATING SCREEN

Plate 2

The exposure of about 1/1000 second was sufficiently fast to stop the motion fairly well, though the test is far from critical due to imperfect focus. The doubling of the image in the narrow regions of overlap is largely concealed by the fact that the lines of the car are mainly parallel to the direction of motion. The effect is clearly seen, however, at the lower edge of the front mudguard and at the upper edge of the windshield. In both cases the amount of doubling is in agreement with calculation, which gives a motion of the car equal to 3 inches during the time of shutter travel, taken as 1/125 second.

In judging the importance of this doubling it should be remembered that (1) it is roughly 15 times as great under the conditions of the test as in normal aerial photography; (2) noticeable doubling is confined to strips less than 0.05 inch wide, or ten percent of the total picture area; (3) the standard 24-inch K-17 camera, which is still widely used for military aerial photography, has no shutter speed faster than 1/150 second.

More complete tests of the shutter could be made by allowing the camera to rotate at known speeds. However, the main objective of the present test was to demonstrate that a model of the proposed shutter could be made without complex machine work, and that the performance of such a shutter was in general agreement with theory. This is shown by Plate 2 to be the case.

The most striking feature of the upper picture of Plate 2 is the series of parallel stripes, which are, of course, due to non-uniform exposure of the negative. This shows that in the present model the screens continue to be accelerated during virtually their entire motion. The result is a gradual decrease in the exposure across the stripes exposed through each slot, and a failure of the two exposures to add up properly in the regions of overlap. Even though this makes the picture quite unsuitable for pictorial purposes, there is very little loss of detail due to inequalities of exposure, since the variations are not abrupt and the total range of exposure is not extreme.

It is believed that the motion of the screens, and hence the density of the photograph, could be made far more uniform than in the present model without unreasonable elaboration of the driving mechanism. No determined effort was made to accomplish this, however, because soon after completion of the preliminary tests reported here the decision was made to continue development of the shutter elsewhere.

Compensating Screen for Printing.

The effect of variations in exposure can be greatly reduced during the printing by introducing a suitably graded screen in contact with the negative. Such a screen can be made by photographing a uniformly lighted surface with the same shutter and lens, and making a positive transparency from the resulting negative. The contrast can be controlled during this process to give the desired degree of compensation. Such a screen can then be used in making prints from any normal negative made with the shutter, so long as the conditions of operation remain the same. Reasonably good registration of the screen and the negative is of course required. Although this would modify the routine of printing as now performed, no serious difficulty should be involved.

The lower picture in Plate 2 shows the degree of correction that was obtained in a preliminary test of this method. The strip at the bottom of Plate 2 shows the appearance of the screen itself.

This method of correcting exposure variations is not demonstrated here as a suggestion that the new shutter could be used without improvement beyond the present model. It would appear both necessary and practicable to obtain sufficiently uniform exposure so that irregularities in direct prints would not be troublesome to the photointerpreter or to the mapmaker. This would still permit some imperfections, however, and it might prove useful to eliminate these when prints were desired for a special purpose, such as the making of mosaics.

II. MODIFICATION OF 24-INCH K-17 SHUTTER.

Abstract

An effort has been made to increase the speed of the standard 24" K-17 shutter by modifications which might be applied to existing shutters.

Simple replacement of the driving spring by a triple spring, which applies a larger torque more efficiently, has been found to decrease the total exposure time by 30%.

Other possible changes are discussed, and their expected effects found to be relatively small.

Tests with the triple spring indicate that its use is practical if a few other changes of a minor sort are made, and if the tendency of the shutter leaves to interfere on closing can be overcome. However, no satisfactory solution of this last condition has been found.

Introduction

The purpose of this study was to increase the speed of the 24-inch shutter by means of alterations which could readily be applied to shutters already in service. It was undertaken as a sequel to the successful modification of the Metrogon shutter for the K-17 camera, which is described in OSRD Report No. 3025 (Section 16.1 Report No. 35) November 1, 1943, "Modification of the Metrogon Shutter to Increase Its Speed."

In the case of the Metrogon shutter a large fraction of the energy of the driving spring was found to be expended in overcoming the inertia of the cam. By redesigning this cam it was possible to reduce its moment of inertia by a factor of three. This change, together with replacement of the plain cam bearing by a ball bearing decreased the exposure from a rated value of 1/300 second to a total exposure of 1/450 and an effective exposure of 1/570 second.

Analysis of the dynamics of the 24-inch shutter showed that neither the cam nor the blades absorbed a large enough fraction of the driving energy so that a simple reduction of the moment of inertia of one part of the shutter would be sufficient. This result was in general agreement with a more complete analysis of the shutter made by William Bender, which was later obtained through Wright Field. Possible changes in the blade assembly and in the cam shaft and bearing are mentioned below, but the most promising method of obtaining a satisfactory increase in speed appears to involve replacing the driving spring and increasing the driving torque.

A triple spring has been developed which can be installed readily and which reduces the total exposure time about 30%. However, it is doubtful whether the blade assembly as now constructed can stand such an increase in speed. Necessary modification of the blade assembly would probably include the use of improved materials or construction of the blades themselves and strengthening of the operating links.

Modification of Driving Spring

The five shutter leaves are mounted independently on pivots. One of them is driven by a connecting link from an eccentric on the operating cam shaft. The motion is passed on to the other leaves by a linkage system which joins each to its neighbors. During an exposure the cam shaft makes one complete revolution, the motion being controlled by three cam surfaces.

The present driving spring receives a total winding of 2 3/4 turns, so that after operation of the shutter it is still wound 1 3/4 turns. This has two disadvantages. Since the driving torque (figured on a static basis) decreases only 36% during the exposure, the cam is driven hard against the positive stop, instead of being allowed to coast to a certain extent during the last part of its rotation. The second disadvantage of this method of winding is the large moment of inertia of the spring that must be used to give a particular initial torque.

The standard spring has 30 coils. If a similar spring with only 10 coils is substituted and given a total winding of only one turn, the initial driving torque is essentially unchanged, but the moment of inertia of the spring is reduced by two thirds. With this change the torque decreases rapidly during the exposure, approaching zero as the cam completes its motion. The result of this change in the driving spring is shown in detail by the curves of Figure 3, which were obtained from oscillograph records and show the amount of light passing through the shutter plotted against time. The curves have been so placed along the time axis as to bring their initial points together.

Although only 66% as much total energy is expended when the 10-coil spring is used, the exposure time is increased but 10%. The smaller amount of energy is relatively more effective, because the moment of inertia of the system has been reduced, and because the force is applied at the time it is most needed, near the start of the motion.

Triple Spring

A simple way of increasing the driving force is to install three identical units like the 10-coil spring discussed above. Such a triple spring has been made and tested. It reduces the total exposure time from 1/150 to 1/210 second, giving an effective exposure of 1/285.

The three new springs are of the same diameter as the original spring, and are wound from wire of the same size. Each has 10 turns instead of 30. The pitch is increased three fold, so that the length of each spring is the same as that of the original spring.

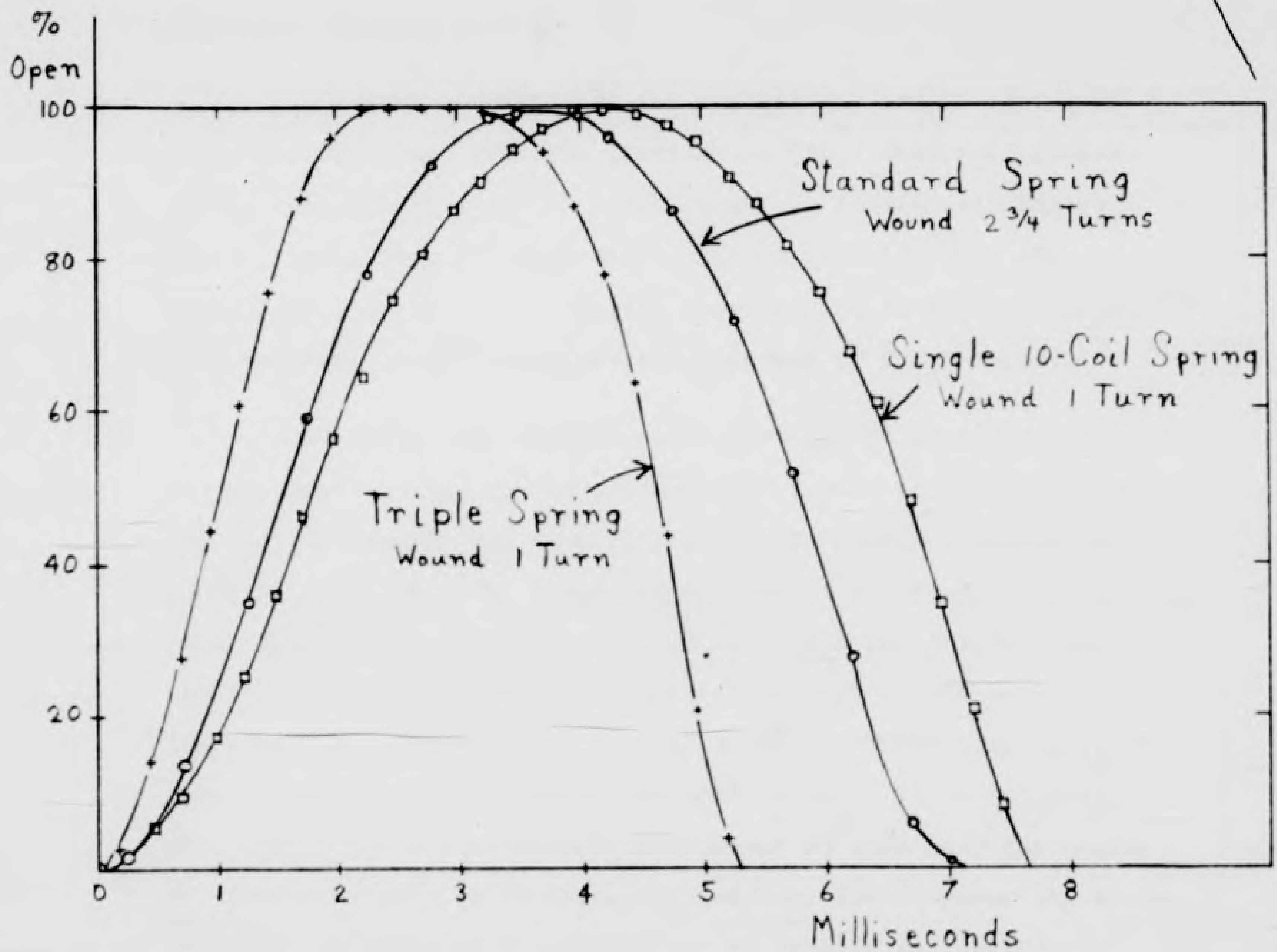


Figure 3. Shutter Tests. Comparison of Springs.

The three units are nested together, and fit into the standard housing with no alterations except the addition of two notches in each of the cups which grip the spring ends. These notches are spaced at 120° intervals from the present single notch which holds the standard spring.

For each operation of the shutter the triple spring is wound one turn just like the standard spring. However, instead of the "initial winding" of 1 3/4 turns, no initial winding is given. The spring is installed in such a position that when unwound it just holds the shutter closed. The total winding before release is therefore one turn instead of 2 3/4 turns.

Since the new springs have one-third as many coils as the standard spring, the torque exerted by each of them when wound one turn is roughly the same as that of the standard spring wound 2 3/4 turns. The total torque at the moment of release is, therefore, three times as great as formerly. With the triple spring the torque decreases rapidly, approaching zero as the cam completes its rotation. Although the initial torque is three times greater than before, the total energy expended is only twice as great. This energy is more favorably distributed in time over the course of operation, most of it being applied near the start of the motion when the cam needs to be accelerated as rapidly as possible.

The moment of inertia of all three springs is essentially the same as that of the original spring. Since the torque for a given angle of winding is about nine times as great, the natural frequency of the new spring system is about three times faster than for the standard spring.

When the triple spring is wound one turn, each coil is deformed approximately the same amount as when the standard spring is wound 2 3/4 turns. Therefore, insofar as the life of a spring depends upon the closeness that it is brought to its elastic limit, there should be essentially no difference between the durability of the new and the old springs.

The triple spring can be wound as much as 1 1/3 turns a few times without deforming it. Although this results in a faster exposure, it is not considered a practicable procedure, since with this winding the spring's life would probably be reduced.

Another triple spring has been tried, in which each unit has 8 coils instead of 10. This gives much the same result when wound one turn as the regular triple spring wound 1 1/3 turns, and is impractical for the same reason.

A summary of results obtained from oscillograph records with various springs and windings is given in Table 1.

TABLE 1. OBSERVED SHUTTER SPEEDS.

	TOTAL EXPOSURE Seconds	EFFECT. EXPOSURE Seconds	EFFICIENCY Per Cent
Standard Spring and winding	.0067 1/150	.0044 1/230	66
10-coil Spring			
wound 1 turn	.0071 1/140	.0048 1/210	67
" 1 1/3 turns	.0062 1/160	.0042 1/235	68
8-coil Spring wound 1 turn	.0071 1/140	.0051 1/195	72
Triple Spring (10-coil springs)			
wound 1 turn	.0048 1/210	.0035 1/285	73
" 1 1/3 turns	.0043 1/230	.0032 1/310	74
Triple Spring (8-coil springs) wound 1 turn	.0050 1/200	.0036 1/280	72

Other Possible Modifications

Modification of Shutter Blade Assembly

Only about one third of the total effective inertia of the system is due to the shutter blades. This means that reduction of the moment of inertia of the blades cannot reduce the total effective moment of inertia of the shutter by more than about 20 percent. Although this gain may be enough to justify the development of lighter materials for the blades, a more important advantage of using such materials would probably be that for a given moment of inertia the blade assembly could be made stronger. This would permit the use of a more powerful driving spring, increasing the shutter speed as described above.

Since the Photographic Laboratory at Wright Field had started an investigation of various plastic materials for shutter blades, relatively little work on this subject has been done here. A few samples of plastic-impregnated fabric were cut to shape and carefully riveted to reinforcing plates patterned after those used to mount the standard spring steel shutter blades. One of these at a time was mounted and driven by the triple spring and standard cam and connecting link. None of the samples lasted more than a few operations. They first became deformed by the driving force acting against the inertia of the outer parts of the blade. As soon as the material had acquired a permanent set, it broke very quickly. One set of plastic blades sent to us from Wright Field, which were tapered at the edges, also failed to last more than a few operations when driven singly in this way.

A promising material for shutter blades is an alloy of aluminum with beryllium, of which a small sample was obtained from Wright Field. This is light and fairly hard and has a very high modulus of elasticity. However, it does not now appear to be available in this country even in small quantities.

The replacement of the present plain pivot bearings, on which the shutter leaves oscillate, by standard Torrington needle bearings has been considered. There is no clear indication that friction is an important factor, but in connection with flutter of the shutter blades (see below) it is possible that pinion bearings that cannot bind would prove helpful.

The links by which the shutter blades are driven can be lightened considerably without loss of strength. Since these links contribute only a few percent to the total effective moment of inertia of the shutter, no appreciable gain in speed would result from such a change. A more profitable alteration in the links may be to strengthen them, and especially to increase the size or hardness of the bearings at their ends. This would prevent the links from breaking down under an increase of driving force.

Modification of the Cam Shaft Assembly

The only promising method of lightening the cam shaft appreciably involves changing the method of construction. The cams are now riveted to the shaft. If the entire unit were cut from a single piece of steel, and then heat treated locally, the mass could be greatly reduced. This would be the same procedure which proved successful with the Metrogon shutter. However, in the present case even if the moment of inertia of the entire assembly could be reduced by 50%, the increase in shutter speed would be only about 15%.

A few less fundamental changes may be suggested. The shutter spring cup has been greatly lightened by cutting away all unnecessary material from the rim, leaving only enough to grip the end of the spring.

The safety collar, so called because it prevents the spring from being over-wound, is a cylinder which fills the space inside the spring. It adds to the effective moment of inertia only to the extent that it is caused to turn by friction. Such friction must result mainly from the fact that the collar is held in place on the cam shaft by the same clip which holds the thrust bearing in adjustment. Any

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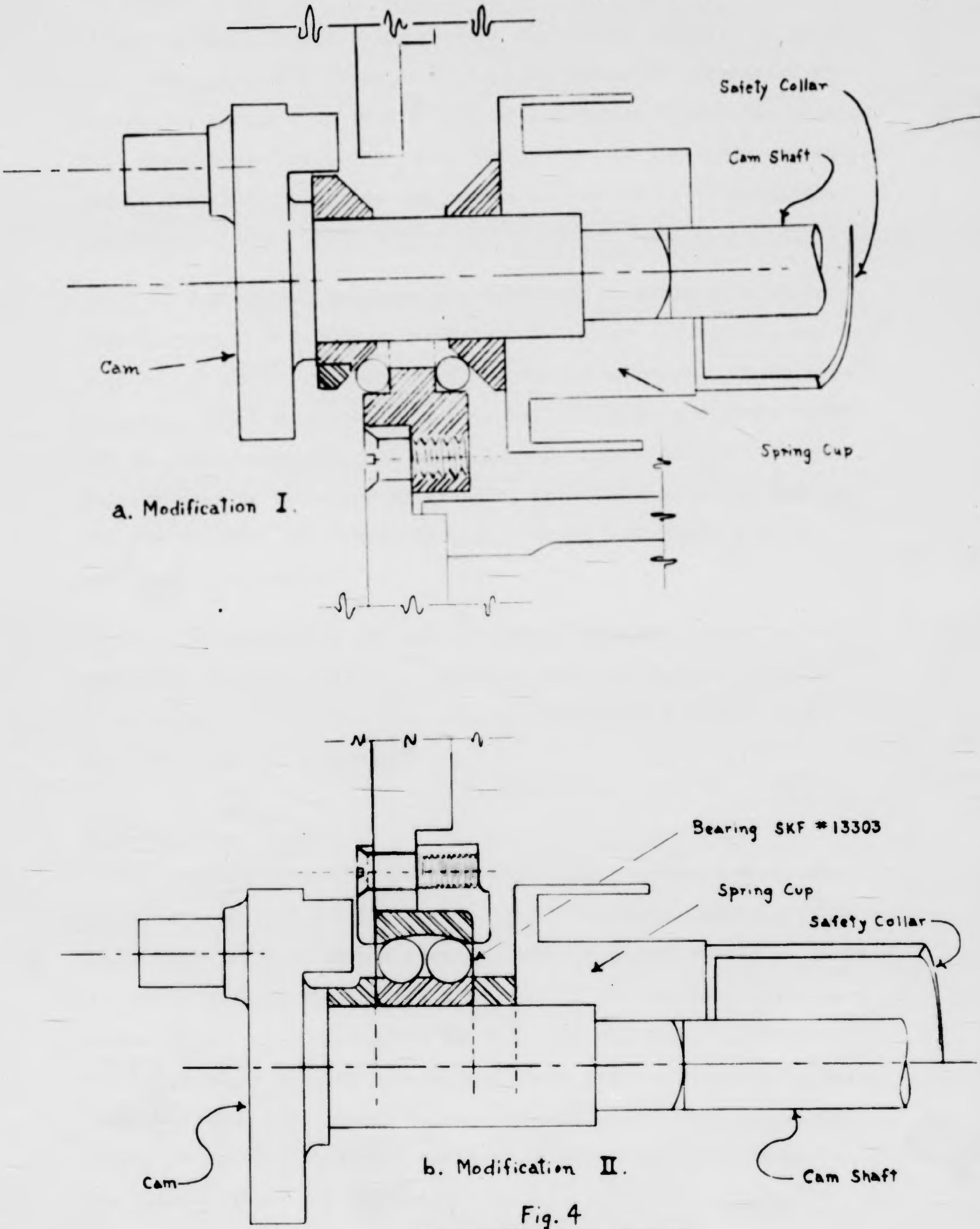

Fig. 4
Modification of Cam Bearing
24" K 17 Aircraft Camera
Mount Wilson Observatory
Scale: 1" = 1/4"

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thrust taken by this bearing presses the collar against the spring clip. The resulting friction could very easily be eliminated by moving the spring clip to the side of the collar toward the bearing. This would leave the collar more nearly free of the shaft and should reduce its contribution to the moment of inertia to a negligible quantity.

The present main cam shaft bearing consists of a plain bearing with a ball thrust bearing. The latter contributes appreciably to the moment of inertia of the entire assembly. These were replaced, first by a specially made ball bearing, and later by an SKF No. 13303 self-aligning bearing. The inner diameter of this bearing must be increased by grinding from 0.315 to 0.342 inch to fit the standard cam shaft. Figure 4 shows both these ways of modifying the bearing.

No detectable change in shutter speed was caused by the change in cam shaft bearing. However, the ball bearing appears to give smoother action, and this may reduce the strain on the leaf assembly and prolong its life.

Flutter of the Leaves

Calculations of the theoretical shutter speed were made, and gave a value about 40% faster than the observed speed. (This is in contrast to Bender's results, which were not available to us at that time.) It seemed possible that if the shutter leaves were deflected out of their normal plane by air pressure, a good deal of energy might be used in stopping their oscillations and bringing them back into that plane, as must be done before they can close. Therefore metal guides were added to restrain the open leaves to one plane. These are shown in Plate 3.

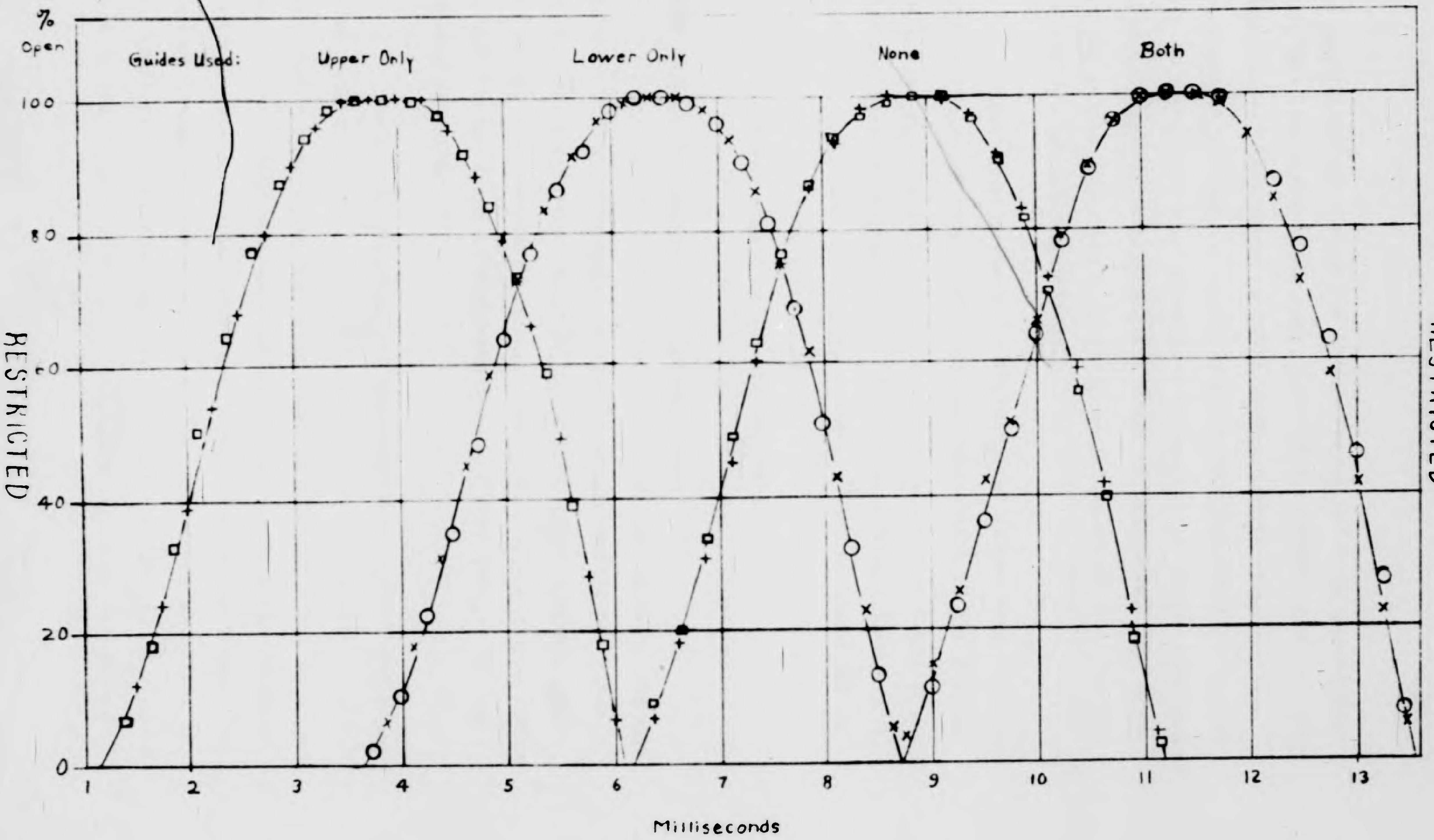
No effect of these guides on the time course of the exposure was found. In Figure 5 curves are plotted for operation of

Plate 3 Shutter with Leaf Guides in Place

Figure 5

24" Shutter. Test of Blade Guides

Triple Spring, Wound One Turn



the shutter equipped with the triple spring (1) with upper guide only, (2) with lower guide only, (3) without guides, and (4) with both guides. Each curve is drawn through points obtained from two separate exposures. The slight discrepancies between the two sets of points for each curve give an indication of the experimental error involved in determining the shape of the curve. The curve without guides indicates a slightly longer exposure, but the difference is scarcely significant.

When first tested, the shutter leaf guides were supported only at the outer ends. After several operations of the shutter, the guides were found to have been forced apart from 0.005 to 0.015 inch and given a permanent set. Spacers were then introduced between the guides and the shutter castings. Two of these can be seen in Plate 3. This support of the inner ends of the spacers had no observable effect on the shutter action.

Life Test of 24" Shutter with Triple Spring.

Two new 24" K-17 shutters were modified by replacing the standard driving spring by the 10-coil triple spring described above. No changes were made in the shutter blade assembly or in the camshaft or camshaft bearing. The effect of the triple spring on the shutter speed of these shutters was very similar to that already described.

One of the shutters was operated a total of 2,725 exposures, the other 225. In both cases the tests were stopped when the shutter blades cut into each other in closing. This is understood to be a frequent cause of breakdown even with the standard shutter. The connecting links are necessarily on one side of the shutter blades, and particularly in the case of the main link to the camshaft crank, they may tend to twist the blades. A curious fact is that with both shutters the interference of the leaves occurred soon after the blade pivots had been lubricated with light clock oil.

The bearings of the operating links showed noticeable wear in the first of the shutters, but this did not prevent satisfactory operation. Other parts of the shutter assembly and camshaft showed no evidence of unusual wear.

The winding mechanism in the camera appears to be able to provide the larger torque required to wind the triple spring. One of the gears showed some wear, but it is doubtful if this would cause trouble.

Considerable difficulty in running the tests was experienced from an unexpected quarter. Occasionally when the trip mechanism in the camera was operated (through the intervalometer) the shutter would fail to fire. The fundamental reason for this was the increased friction on the catch which holds the cam in the wound position and then releases it. Force to release this catch is provided by a spring in the camera body, which in turn is released by a solenoid operated from the intervalometer. This spring needs to be strengthened, either in the camera or by means of a booster spring which could be added to the shutter. In either case trouble may still be caused by flexibility of the connecting shaft between camera body and shutter.

If failure of the tripping mechanism to operate meant only the loss of a picture it might not be serious. But the camera proceeds at once to wind the shutter again. When the spring becomes tight on the safety collar a shearing pin breaks in the camera, putting it entirely out of operation until the pin is replaced.

In conclusion, although the triple spring itself can be installed very simply, it probably could not be used successfully without making some other changes as well. The tests that have been made indicate that these changes include as a minimum strengthening of the tripping mechanism and some modification of the shutter leaves which will prevent them from interfering. The shutter blade links and their bearings may also need strengthening.

Some of these changes are straightforward, but the possibility of increasing the stiffness of the shutter blades without increasing their moment of inertia is more doubtful. Partly because of this difficulty and partly because of the increasing use of focal plane shutters by the Army, further work on this project has been discontinued.